LA-UR-18-31790

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Title:	Level 2 Milestone MRT 6218: Improve Nuclear Measurements on the NIF
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Intended for:	Report
Issued:	2018-12-19

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Level 2 Milestone MRT 6218:
Improve Nuclear Measurements on the NIF

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This report documents the completion of the Inertial Confinement Fusion, Level 2 Milestone MRT 6218, "Improve Nuclear Measurements on the NIF." The three completion criteria are, "1) Complete Operational qualification (OQ) of Pulse Dilation PMT on the Gas Cherenkov Detector in the Well DIM at NIF, 2) Measure highly resolved (temporal magnification >= 5x) gamma signals for Carbon (ablator) history, 3) Measure highly resolved (temporal magnification >= 5x) gamma signals for DT fusion reaction history."

1. Operation Qualification (OQ) of the Pulse Dilation PMT on the Gas Cherenkov Detector in the Well DIM at NIF, was achieved on shot N180912-001 in which the control of timing & gain of the Pulse Dilation PMT was demonstrated.

2. A 10x temporal magnification of carbon (ablator) history was achieved on shot N180930-001 in which Gas Cherenkov Detector was set to a 2.9 MeV energy threshold. The carbon ablator history signal was temporally-separated from the holraum background signal, thanks to the 10x magnification of the Pulse Dilation PMT. Highly-resolved ablator history will improve the accuracy and precision of the ablator areal density measurement currently being performed by the complementary GRH at NIF.

3. A 10x temporal magnification of DT fusion reaction history was achieved on shot N181028-001 in which Gas Cherenkov Detector was set to a 8 MeV energy threshold. A background signal began to interfere with DT Cherenkov signal. However, the dilated DT signal was still higher than the background signal by more than a factor of 5. The burn width of the DT reaction history measured from the Pulse Dilation technique agreed with the GRH measurement within error bars. However, 10x higher temporal magnification enabled the observation of a non-Gaussian (fast rise and slow fall), as well as other features in the DT burn history. The highly-resolved burn history will be important data for better understanding of NIF implosions.

MRT 6218, “Improve Nuclear Measurements on the NIF.”

Gas Cherenkov Detector (GCD) and Gamma Reaction History (GRH) have been developed at LANL for over a decade and have been a workhorse for Inertial Confinement Fusion program. GCD/GRH have inherent temporal dispersion on the order of only ~10 ps, however this fast time response is essentially squandered in coupling the optical Cherenkov signal to the current state-of-the-art photomultiplier (PMT) which are only capable of ~100 ps resolution. Revolutionary new Pulse Dilation (PD) technology is now enables PMTs to diagnose flashes of light on the picosecond time scale. The primary motivation for PD-PMT project is to take better advantage of GCD/GRH measurements of ICF gamma-ray signals by providing highly-resolved Carbon Ablator History and DT Fusion Reaction Histories. In the near future, PD-PMT will also be used to diagnose the signature of alpha particle heating and failure modes that impede the likelihood of achieving fusion ignition.

Completion criterion #1: Operation Qualification (OQ) of the Pulse Dilation PMT on the Gas Cherenkov Detector in the Well DIM at NIF

1-1) Brief introduction to Pulse Dilation PMT

In the innovative PD-PMT scheme shown in Figure 1, the incident photons are converted into a photoelectron bunch in the same manner used in the conventional PMT. The unique idea is that the photoelectron bunch experiences a ramped-down accelerating voltage, so that the later electrons experience a less acceleration than early electrons. The resulting differential velocity allows the incident signal bunch to spread along the axis of a magnetically confined drift tube, as it travels to the anode tens of centimeters away. By the time the electrons reach the anode, the bunch can stretch by up to a factor of 40. Subsequently, a slower signal is recorded by the oscilloscope which can then be recompressed back to the original time scale, allowing measurements more than 10 times faster than in the conventional PMT technique.

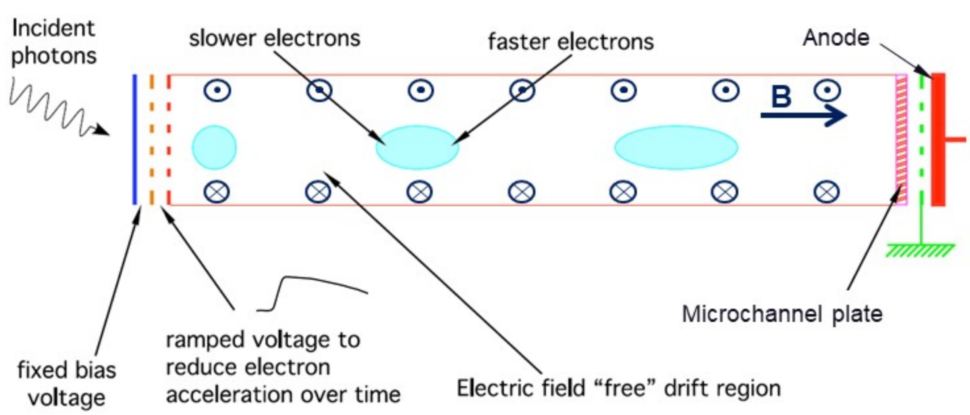


Figure 1- Pulse Dilation Photomultiplier Tube (PD-PMT). A differential velocity is applied to a photoelectron signal bunch so that it can be dilated as it passes down a drift region before being amplified at the MCP and collected at the Anode where it can then be measured using an oscilloscope.

1-2) Calibration of Pulse Dilation PMT at AWE Orion Laser Facility

A double short pulse laser calibration test was performed at AWE Orion facility (Figure 2a). Figure 2b shows the raw data from a double pulse with 135 ps peak-to-peak spacing. The blue "Undilated" trace is taken with the PD-PMT operated in dc mode as a standard PMT and results in the double pulse just barely being resolved. The red "Dilated" trace is a measurement of the same double pulse during the dilation ramp. The dilated signal is recompressed (~20x in time) to match the undilated peak spacing resulting in a highly resolved double peak structure. The resolution of the PD-PMT was found by reducing the spacing between double laser pulses and determined to be slightly less than 10 ps.

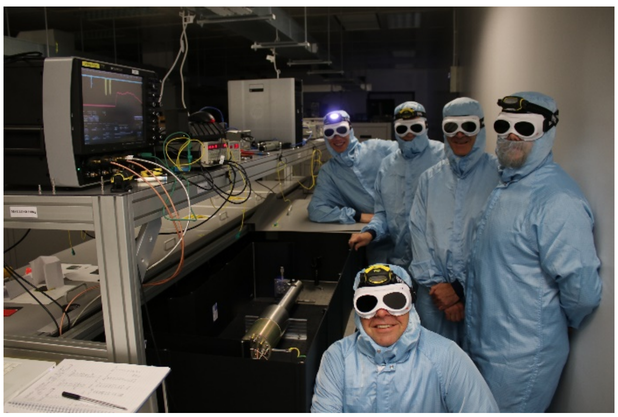


Figure 2a: Team of AWE, Kentech and LANL scientists (Hans Herrmann) characterizing PD-PMT on the ORION Laser at AWE. PD-PMT can be seen as the long, cylindrical tube mounted on the optical table by the shoulder of the nearest individual.

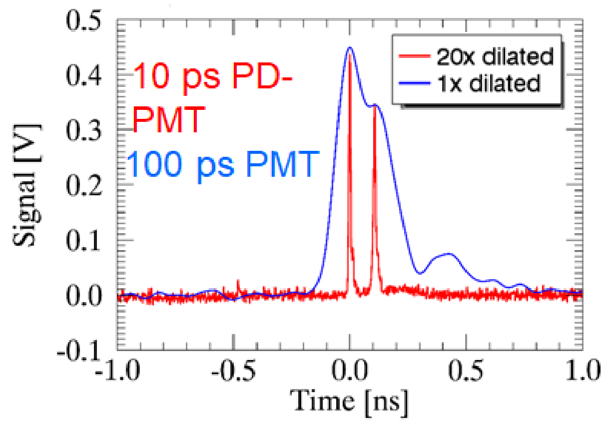
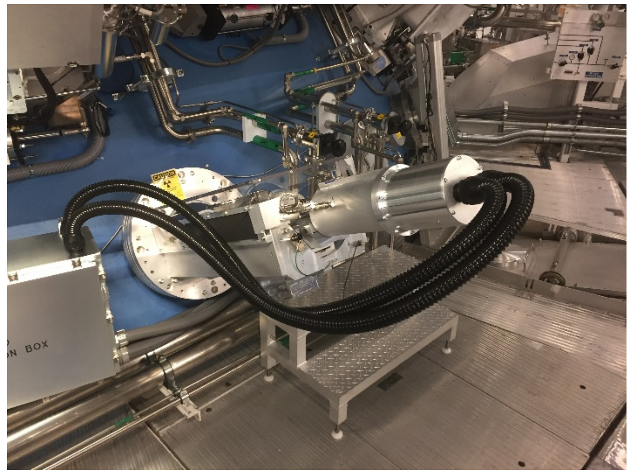


Figure 2b: Two optical pulses separated by 135 picoseconds clearly resolved by PD-PMT (red curve). Standard PMT (blue curve) is just barely resolvable the two optical pulses.

1-3) Installation of Pulse Dilation PMT in the back end of the Gas Cherenkov Detector

LANL ICF program has been directing the development of this revolutionary PD-PMT technology, collaborating with Kentech Technologies LTD, Photek LTD, Sydor Instruments, LLNL, AWE, and General Atomics. During the first installation of PD-PMT on NIF (April 2018), LANL team found that physical damage occurred during shipping from UK, causing an internal electrical short, which required repair from the manufacturer. NNSA approved a delay to move the L2 Milestone (#6218) to the end of 12/2018. After the repair on Aug 2018, the PD-PMT was re-installed into the back end of the GCD on NIF, completing the Installation Qualification (IQ).

Figure 3: PD-PMT installed in the back end of the Gas Cherenkov Detector on the National Ignition Facility (Aug 2018)



1-4) Operation Qualification on shot N180912-001

Operation Qualification (OQ) of the PD-PMT on the GCD in the Well DIM at NIF, was achieved on shot N180912-001 in which the control of timing & gain of the PD-PMT was demonstrated. The N180912-001 was an indirect-drive exploding pusher, dedicated to diagnostic developments purpose. From the onset of DT fusion at the center of capsule, DT neutrons emit into 4π directions. When DT neutrons interact with surrounding materials, such as the ablator shell, hohlraum, cooling assembly, or even diagnostic snouts placed close to the capsule; an intense gamma-ray signal is produced (neutron-induced gamma-rays or simply n-gammas). The n-gammas produced from this interaction are relatively low in energy, typically less than 10 MeV. Since FY17, the GCD equipped with a standard PMT has routinely measured n-gamma signals. In Figure 4, blue trace shows the example data from a previous indirect-drive N170910-001 shot. The first peak around 0 ns is from capsule n-gammas and the later peaks, around 3 – 10 ns, are mostly from diagnostic snouts. For OQ purpose on the PD-PMT, the GCD was set up the same as the previous N170910-001 shot, but dilation was turned on around 8 ns. Our predictions were confirmed and the n-gamma signals between 8 – 10 ns were dilated (reduction in amplitude) due to 10x dilation (red trace in Fig. 4). At this stage, our timing uncertainty is within 300 ps, enough to accurately to participate in all NIF high-yield shots.

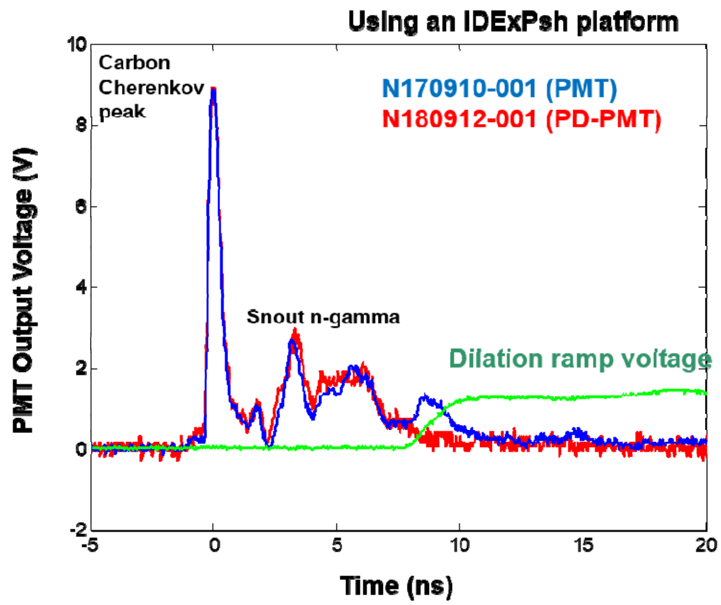


Figure 4: The capability of dilation timing & gain was demonstrated from N180912-001 NIF shot, where dilation begins around 8 ns.

Completion criterion #2: > 5x temporal magnification of carbon (ablator) history

A 10x temporal magnification of carbon (ablator) history was achieved on shot N180930-001, a BFScaleUp series producing a high yield in the order of 1E+16. To capture a 4.4 MeV carbon ablator gammas the GCD gas pressure was set to 2.9 MeV energy threshold. While the carbon ablator gammas are intense in strength, they are interfered with background hohlraum and cooling assembly signals which are only a few mm (~ 80 ps in time delay) away from the capsule. The existing NIF detector GRH separates the carbon ablator signal from hohlraum and cooling assembly by using a differential energy thresholding (2.9 MeV vs. 4.5 MeV); however, GRH is not able to separate gammas in temporal manner. Figure 5a shows the raw data from PD-PMT. The first signal recorded around 98 ns is a pre-cursor (not Cherenkov) from the carbon ablator gammas interacting directly with the PD-PMT. The second portion of signal from 99 – 102 ns is a Cherenkov signal originating from the carbon ablator, hohlraum and cooling assembly. The second signal is stretched out over 3 ns (from 99 – 102 ns) as a result from a 10x dilation effect. Figure 5a raw data clearly shows that a pre-cursor and a Cherenkov peak are well separated in time. Figure 5b's blue curve shows a processed data which was obtained by recompressing the dilated data (red trace in Fig 5a) by a factor of 10x. The recompressing process was performed using a calibrated dilation profile (green trace in Fig. 5b) from AWE. Figure 5b analysis shows that our dilation time windows was turned on at the rise of carbon ablator gammas and remained on about 1 ns after the peak, well capturing the whole signal.

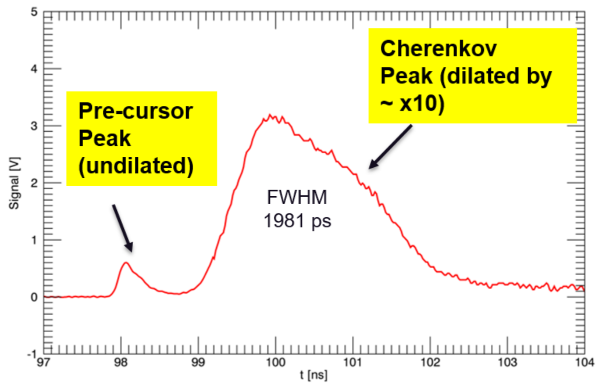


Figure 5a Raw data shows main Cherenkov peak are well separated with the pre-cursor (background)

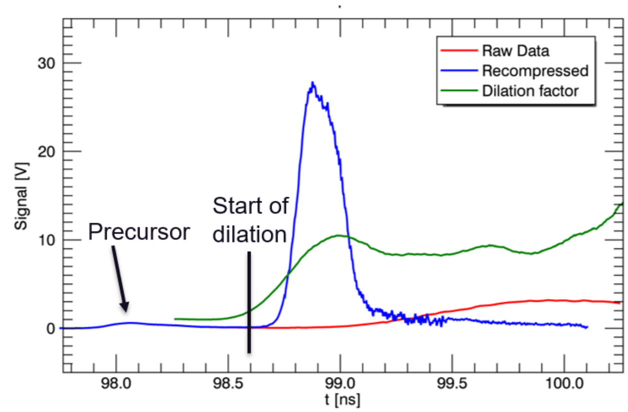


Figure 5b Reprocessed data shows that dilation time window (green trace) was capturing whole signals (blue trace).

In order to qualify the PD-PMT data, we compared the GCD PD-PMT data with the GRH 2.9 MeV energy threshold data. In Fig. 6, orange trace is a PD-PMT data and green trace is the GRH data. While both gamma detectors show the same full-width of half-maximum, the 10x magnification of the PD-PMT reveals that the carbon ablator history signal was temporally-separated from the holraum background signal. Highly-resolved ablator histories will improve and complement the ablator areal density measurement currently being performed by a GRH at NIF.

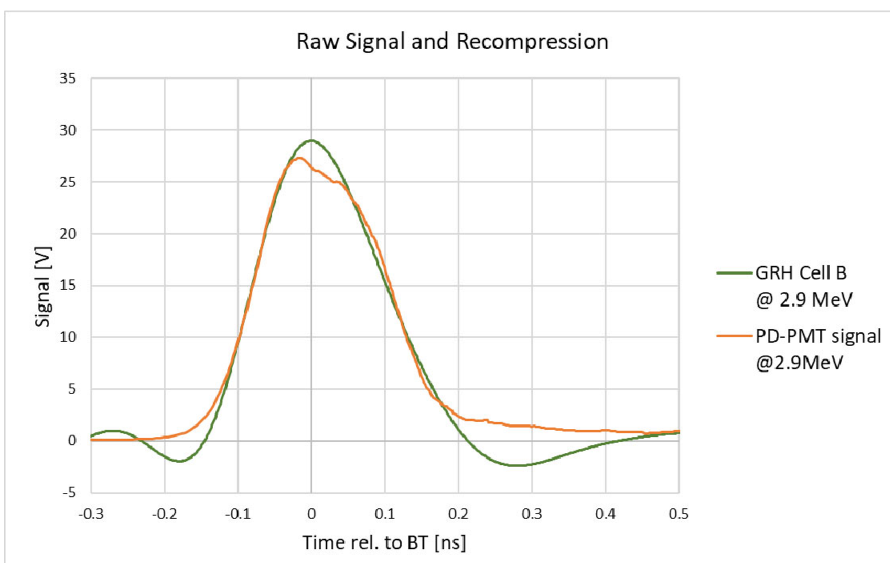


Figure 6: Figure 8: Carbon ablator history obtained from GCD PD-PMT (orange) and GRH PMT (green), confirming higher-temporal resolution of GCD PD-PMT and revealing temporal separation of carbon ablator and hohlraum/cooling assembly background

Completion criterion #3: > 5x temporal magnification of DT fusion reaction history

Since FY17, GCD has used a regular PMT to measure DT fusion reaction history by setting GCD's gas pressure to 8 MeV energy threshold. Unlike the carbon ablator measurement using a 2.9 MeV setting, the DT fusion measurement at 8 MeV was challenging due to interfering background signal from the pre-cursor and neutron-induced gammas. Figure 7a shows an example of previous GCD PMT data obtained from N170827, showing that the pre-cursor peak (first peak) was approximately twice of the DT fusion signal (second peak). Both peaks were not fully separated from each other even with the state-of-art 100 ps temporal resolution of Photek PMT. In addition to the pre-cursor background, neutron-induced gammas (signals shown between 4 – 15 ns in Fig. 7a) are about 20 - 25% level of the DT fusion signals (second peak in Fig. 7a).

For the N181028-001 shot the GCD pressure was set to the same 8 MeV as N170827, and the dilation window of the PD-PMT was set to start between the pre-cursor and main DT peak. The dilation was a success and the 10x temporal magnification of DT fusion reaction history was achieved for N181028-001. The pre-cursor interference was reduced by separating the pre-cursor and DT fusion peaks, taking advantage of high-temporal-resolution of the PD-PMT (10 ps). The neutron-induced gammas background signal still interfered with the dilated DT Cherenkov signal (second peak in 6 – 8 ns range), but the dilated DT signal was still higher than the background signal by more than a factor of 5.

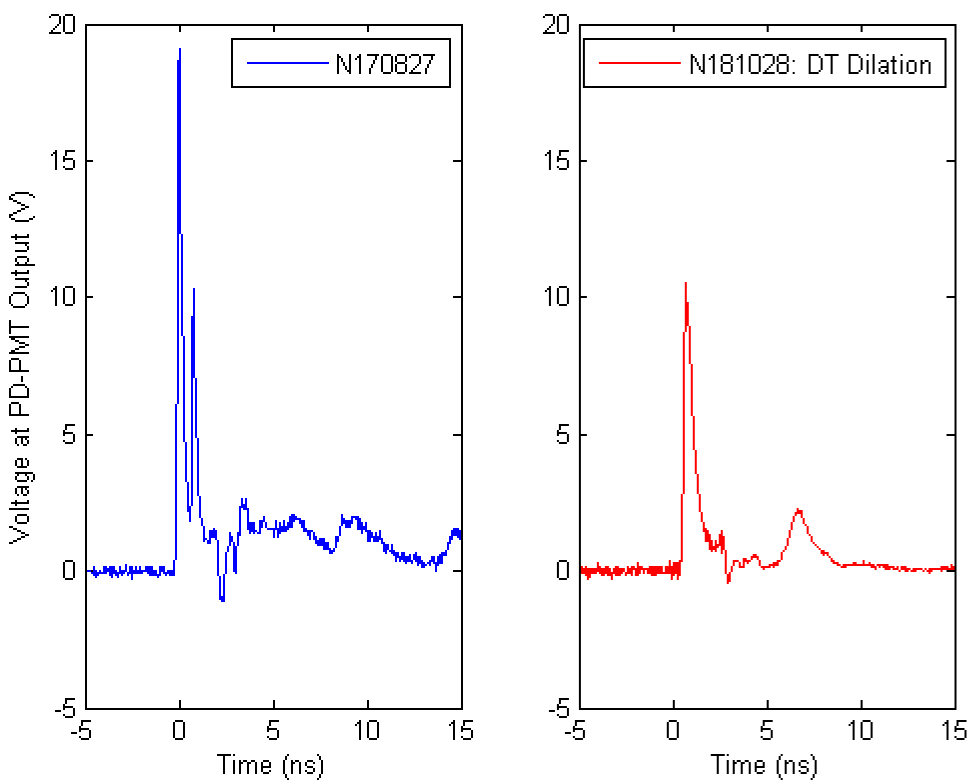


Figure 7: (left) GCD PMT mode measuring DT burn history on N170827. (right) GCD PD-PMT mode measuring DT burn history on N181028. PD-PMT was able to manage precursor background (first peak) by high-temporal resolution.

As we did for a carbon ablator study, we applied a recompression data-process to the dilated DT fusion peak (Fig. 7b signal in 6 – 8 ns time) and obtained the DT fusion reaction history from N181028-001 (HDCScaleUp series). Figure 8's blue trace shows about 100 ps rising time and 200 ps falling time from reaction history. In Fig. 8, GRH data during the same shot was overlaid with the PD-PMT for direct comparison purpose. The burn width (full-width of half maximum) of the DT reaction history measured from the PD-PMT technique agreed with the GRH measurement within error bars. However, 10x higher temporal magnification enabled the observation of a non-Gaussian (fast rise and slow fall), as well as other features in the DT burn history. In the future, more data will be taken for all NIF high-yield campaigns and such non-Gaussian burn history will be further explored in details. The highly-resolved burn history will be important data for better understanding of NIF implosions.

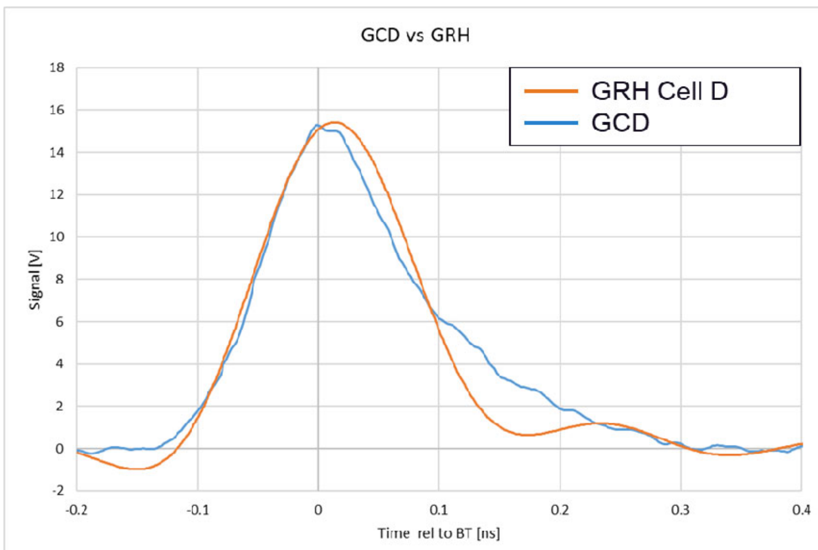


Figure 8: DT reaction history obtained from GCD PD-PMT (blue) and GRH PMT (orange), confirming higher-temporal resolution of GCD PD-PMT and revealing non-Gaussian feature (fast rising, slow falling) burn history of N181028